Wide Bandgap Semiconductor RF Electronics Technology

DARPA/MTO Industry Day

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Purpose of briefing

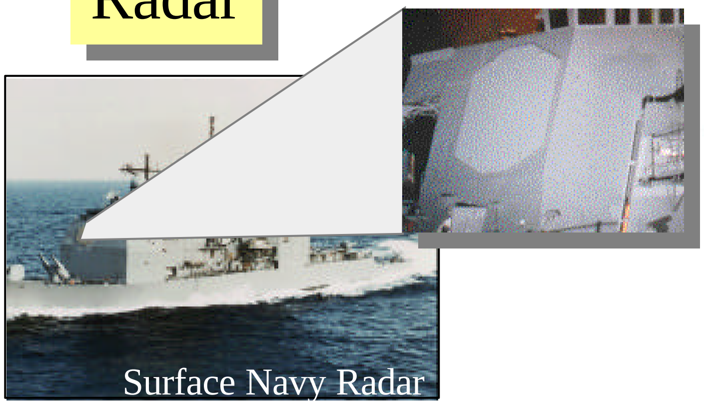
Overview current state-of-the art of SiC and AlGaN RF Electronics Technology

Briefing Outline

- Highlight Tri-Service WBG RF Electronics Applications
- Present State-of the-Art and Technical challenges
  - WBG RF Technology
- Summary

Multiple DoD Platforms Will Benefit from WBG RF Technology

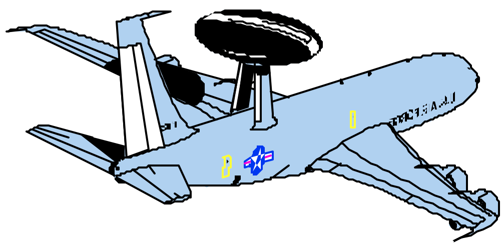
Radar



Surface Navy Radar

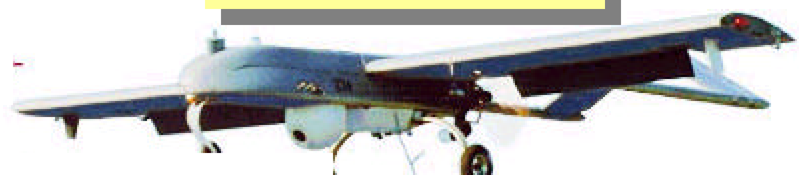
F/A-18 AESA

JSF



AWACS

Tactical UAV

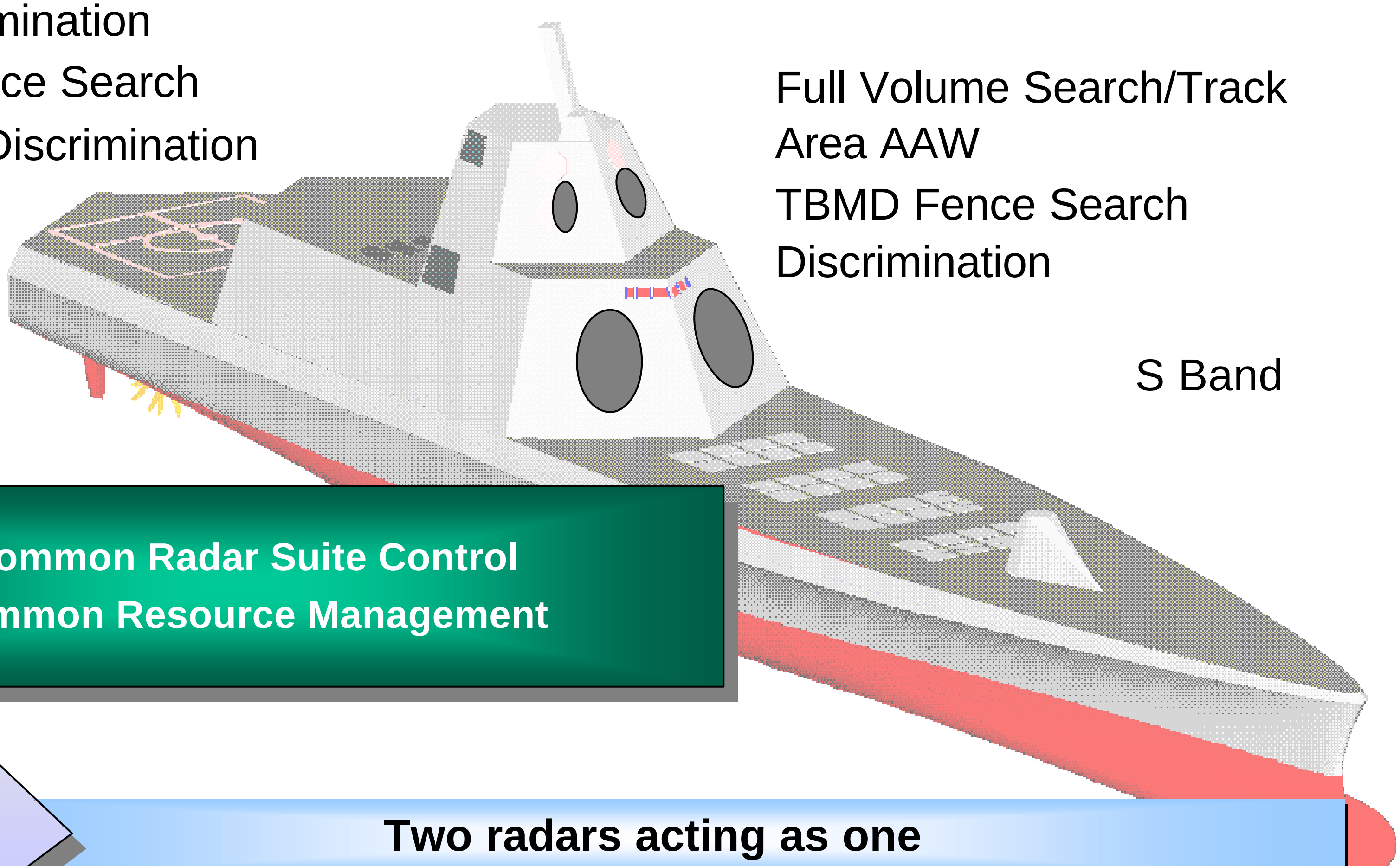


Decoys, jammers, seekers

Navy Vision: Theater Air Dominance Cruiser

Ship Defense Horizon Search/Track
Target Illumination
TBMD Fence Search
Precision Discrimination

X Band



Full Volume Search/Track
Area AAW
TBMD Fence Search
Discrimination

S Band

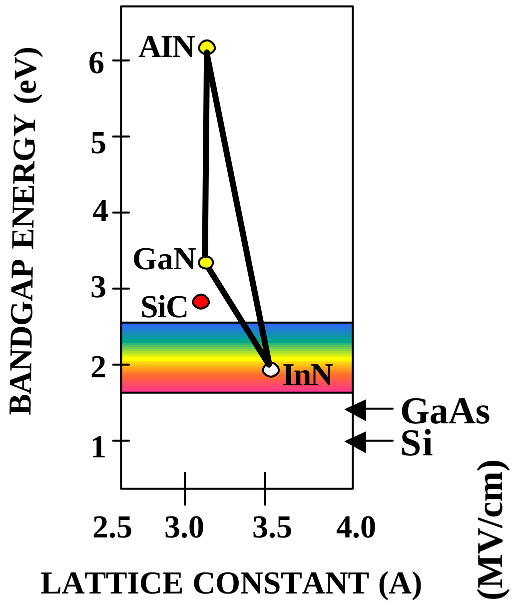
Common Radar Suite Control
Common Resource Management

Two radars acting as one

Power-aperture-gain requirement drives WBG solutions

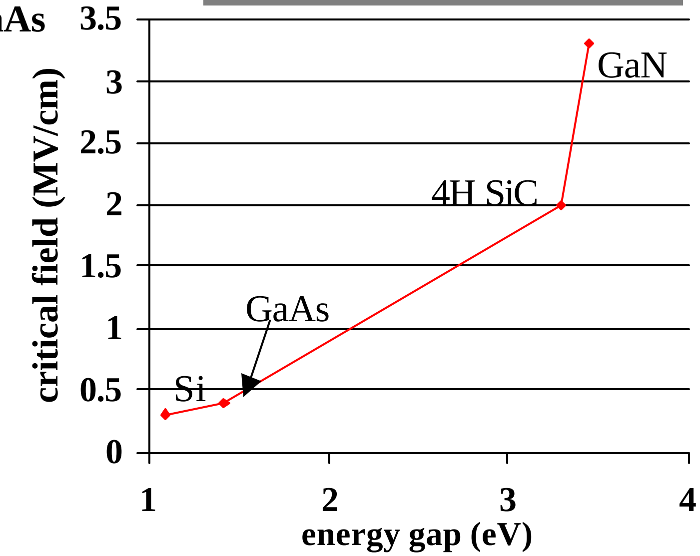
Enabling Properties of WBG

bandgap for optical emission



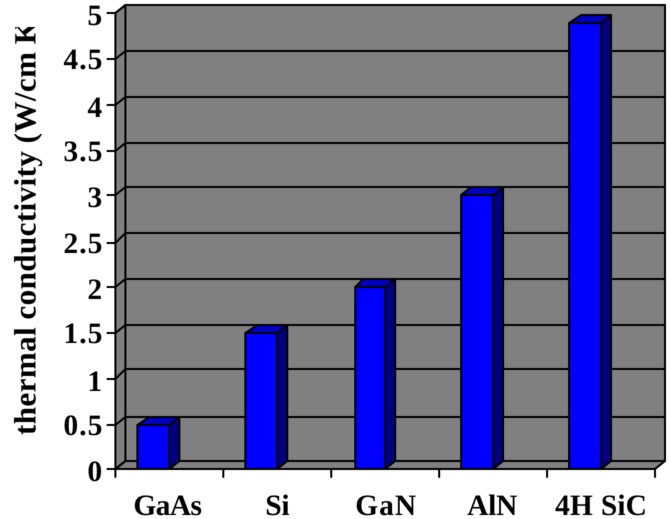
Short wavelength light emitting diodes, lasers, and detectors

critical electric field 10x Si and GaAs



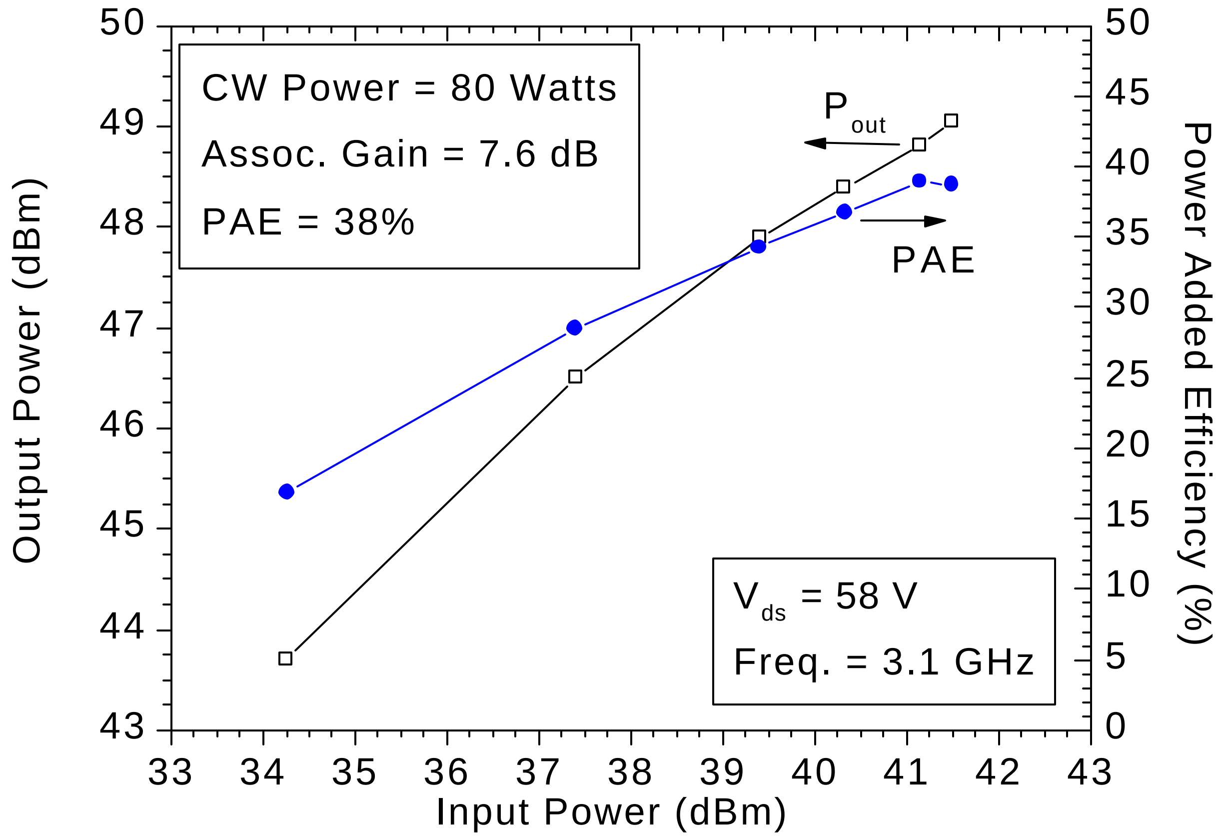
High voltage operation

SiC thermal conductivity 7x GaAs



High power operation

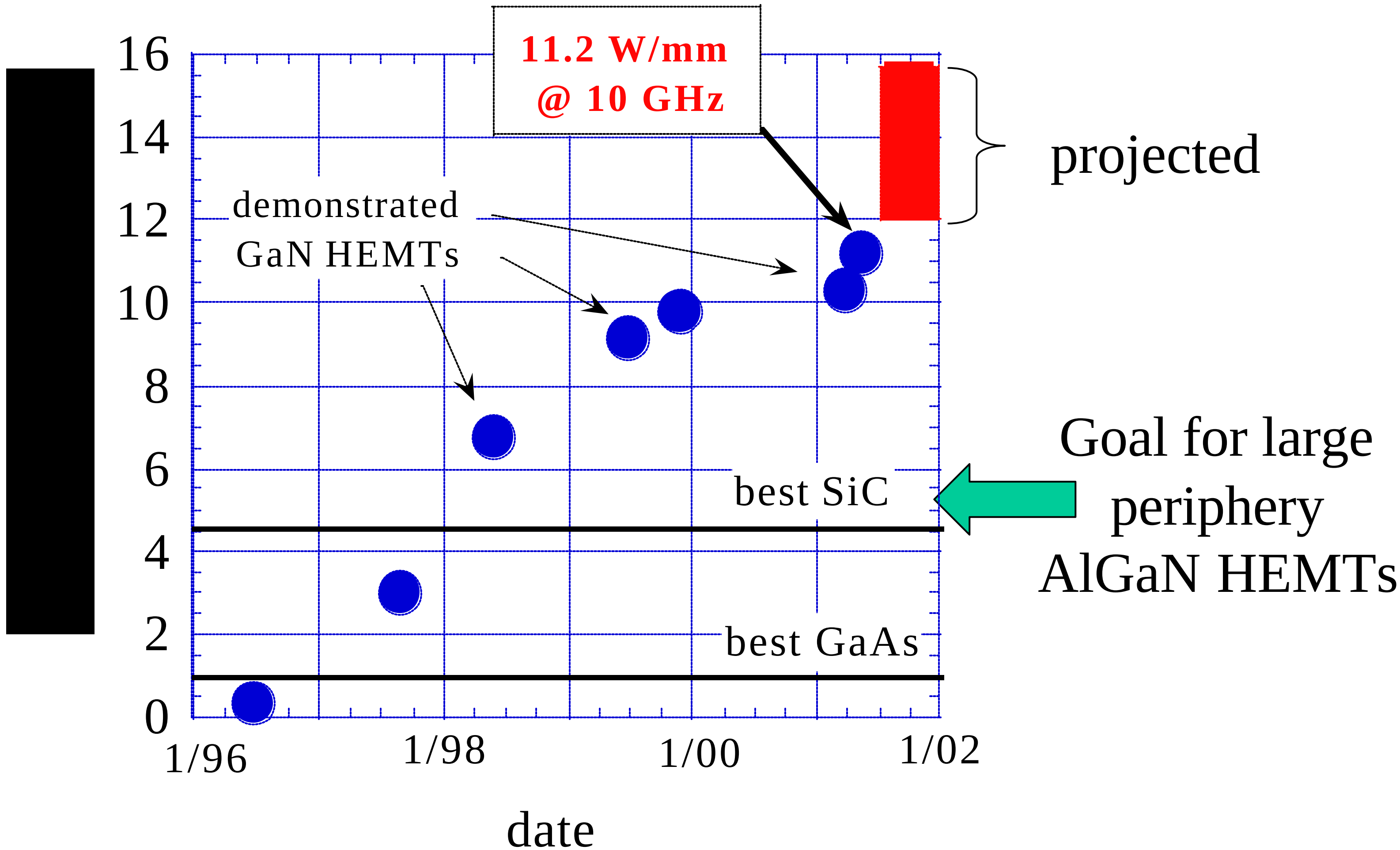
SiC MESFET with 80 Watts CW at S-Band



- 80 watts CW peak power and 38% PAE at 3.1 GHz from a single 1 mm x 4 mm SiC chip, 48-mm FET (>5x GaAs FET)

SiC MESFET work supported ONR

GaN HEMT X-band Power Density

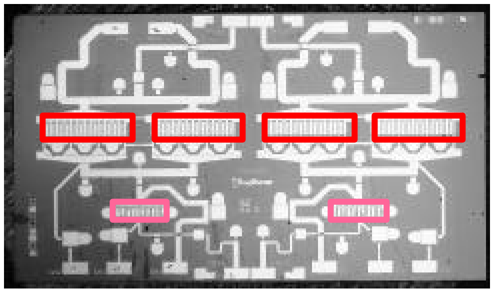


Data for small periphery transistors validates potential

WBG RF Devices Enable High Performance Amplifiers

10 W X-band GaAs PHEMT amp

5.7mm x 3.3 mm

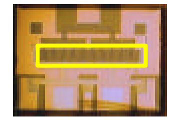


7V @ 75 mA/mm 40% ? pa
~ 20mm total gate periphery
output resistance ~ 4.6?

Best in Class GaAs Amplifier

Same power at >10x the impedance

10 W X-band GaN HEMT Device



1.6mm x 1.2 mm

30V@ 223 mA/mm 46% ? pa
2mm gate periphery
output resistance ~ 67?

Higher impedance enables high efficiency and wide bandwidth

5-10x the power in same transistor size

Higher power at same dimension maintains manufacturability

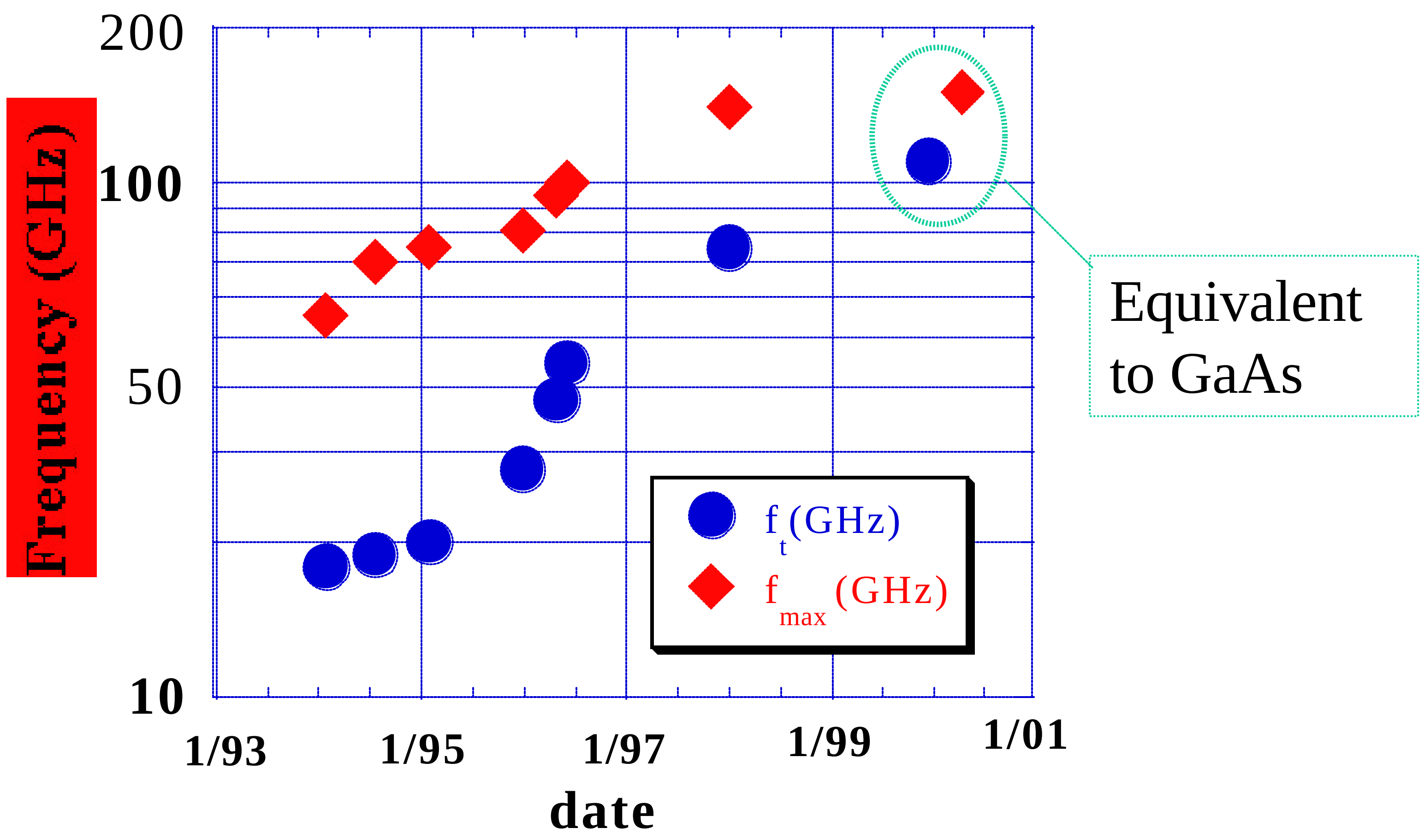
40 W (pulsed) X-band GaN HEMT Device

0.7mm x 4mm (~1/2 GaAs output stage)

55V@ 283 mA/mm 20% ? pa
12mm gate periphery
output resistance ~ 16?

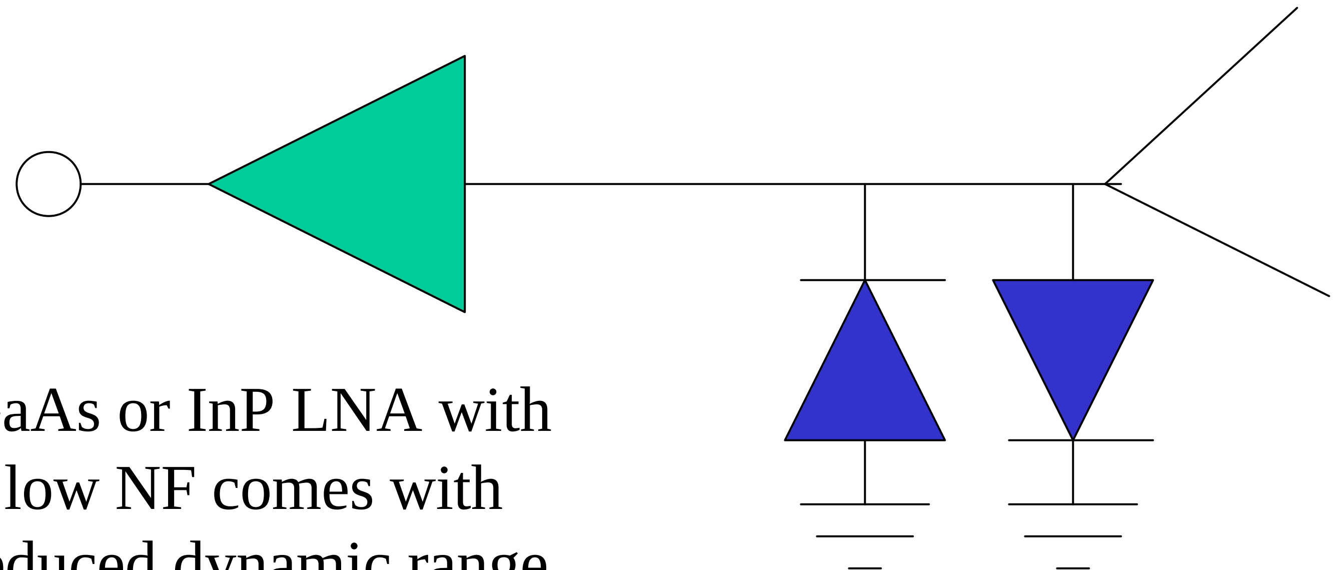
AlGaN HEMT work supported ONR and AFRL

AlGaN HEMT small signal performance



Higher frequency operation predicted

High Dynamic Range Robust LNA



GaAs or InP LNA with
low NF comes with
reduced dynamic range

Limiter
0.5 to 2.0 dB loss
==>> NF

AlGaN HEMT LNA:

- **good n_s? $_e$and large inter-valley energy (1.5 eV) enables low NF**
- **large critical field enables simultaneous large dynamic range**

Robust LNA Figure of Merit

$$RLNAFOM \; ? \; \frac{GV_{br}}{NF_{\min}}$$

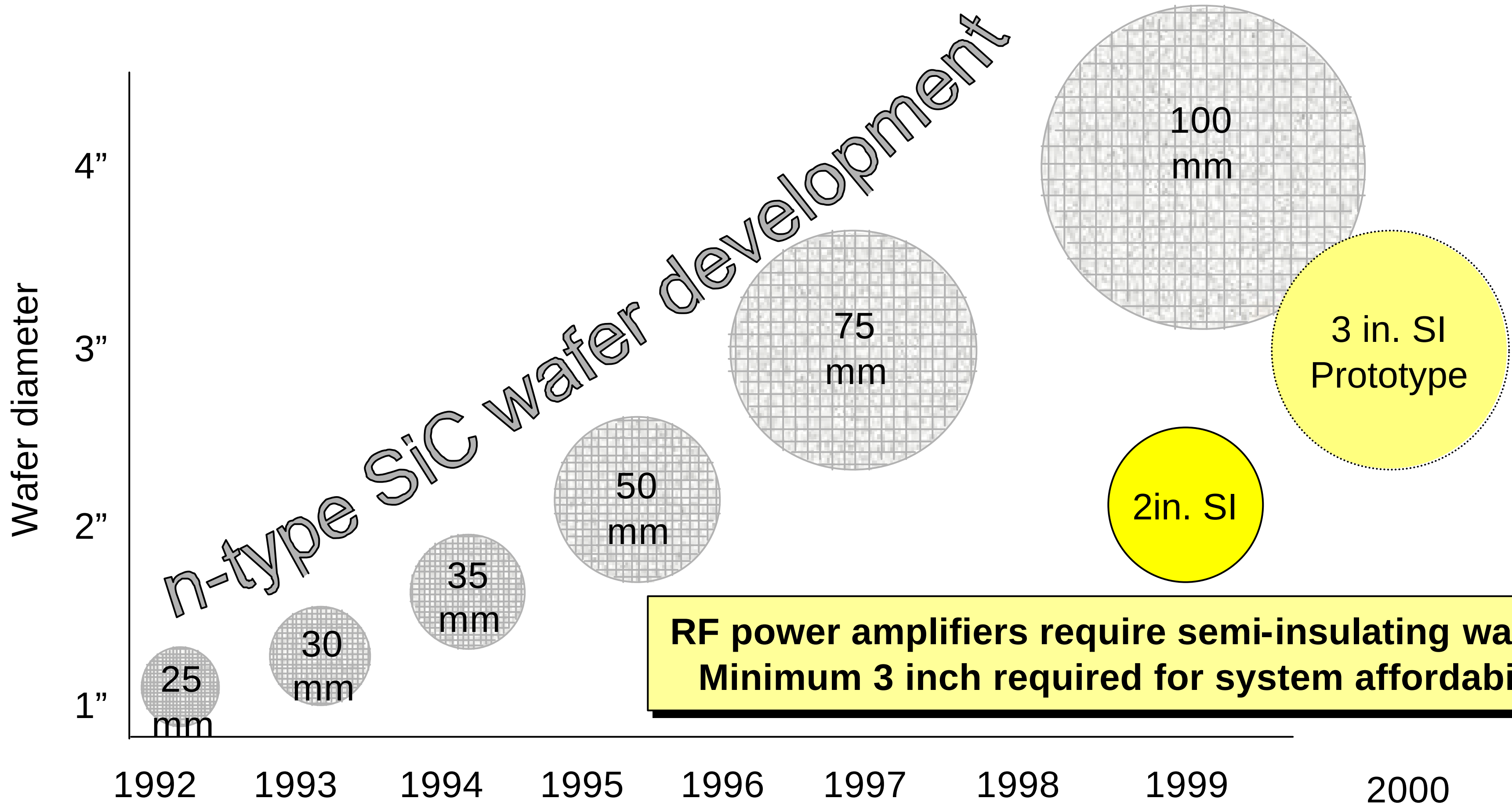
Metric	GaAs pHEMT	InP HEMT	GaN HFET
Minimum NF @ 10GHz	~ 0.5 dB	< 0.3 dB	0.6 dB
Associated Gain	14 dB	18 dB	13.5 dB
Breakdown Voltage	~ 4 V	~ 3 V	>50 V
FOM = GV_{th}/NF	112	180	1125

Table adopted from C. Nguyen, et al., Nitride Workshop, Richmond, VA, March 2000.

WBG RF technology challenges

- Semi-insulating substrate size and quality
- Epitaxial material quality and repeatability
- Device process technology
- Device stability and reliability
- Physical device modeling
- Thermal management

Historical increases in R&D n-type SiC wafers: semi-insulating wafers lag behind



RF power amplifiers require semi-insulating wafers- Minimum 3 inch required for system affordability

Note: SiC active devices require 4H, GaN-on-SiC can employ 4H or 6H SiC

SI-SiC substrate trapping

- Vanadium doped SI-SiC has deep traps accessed under high bias operation that degrade RF performance (only discovered during RF power device development).

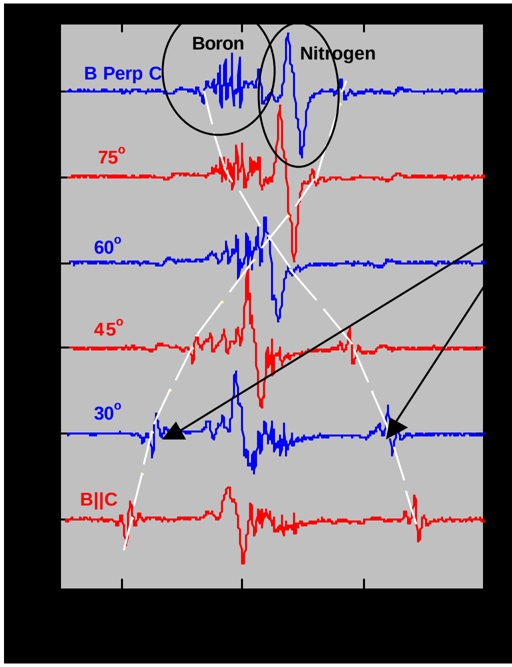
- Vanadium doping degrades bulk crystal quality due to local stress and reduces wafer yield/boule.

- Substrate traps are most evident in SiC MESFETs via degraded efficiency and power output.

- AlN nucleation layer (E_g = 6.2 eV) used for AlGaN HEMTs on SiC significantly isolates HEMTs from traps in SiC wafer. Impact of SiC wafer quality on AlGaN HEMTs has not been fully quantified.

Semi-Insulating “High Purity” SiC

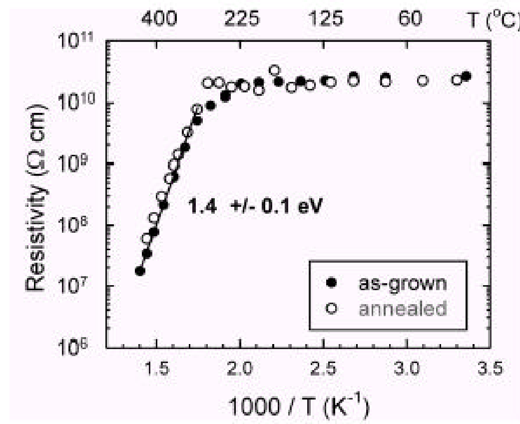
4H-HPSI SiC

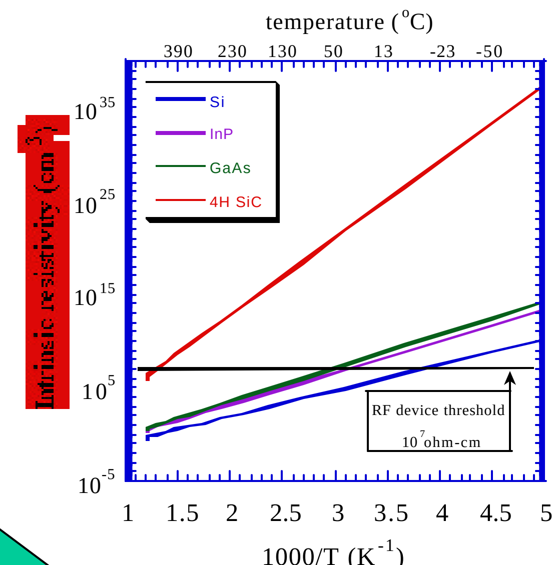


C-vacancy?

Advantages of high purity SiC:

High resistivity, low loss tangent for RF devices
High thermal conductivity for heat dissipation
Low extrinsic defect density
Enables lightly doped substrates for vertical, full wafer, power switching devices





new “intrinsic” defect identified in Ultra High Purity SiC

Potential “intrinsic” deep level defect observed in HTCVD SiC

Goal:
Insulating “intrinsic” SiC

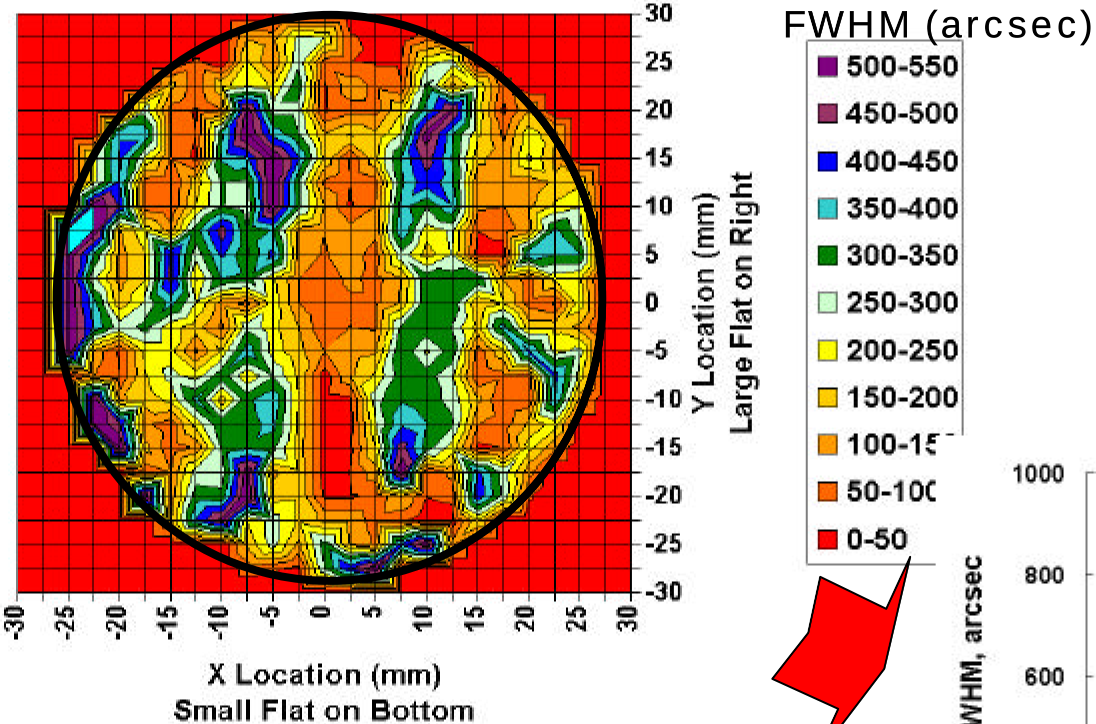
Technical issues:

Reactor component purity
Source material purity
Stoichiometry control of intrinsic defects
Three regimes for growth:
- Elemental Melt+gas
- SiC melt+ gas
- gas+gas

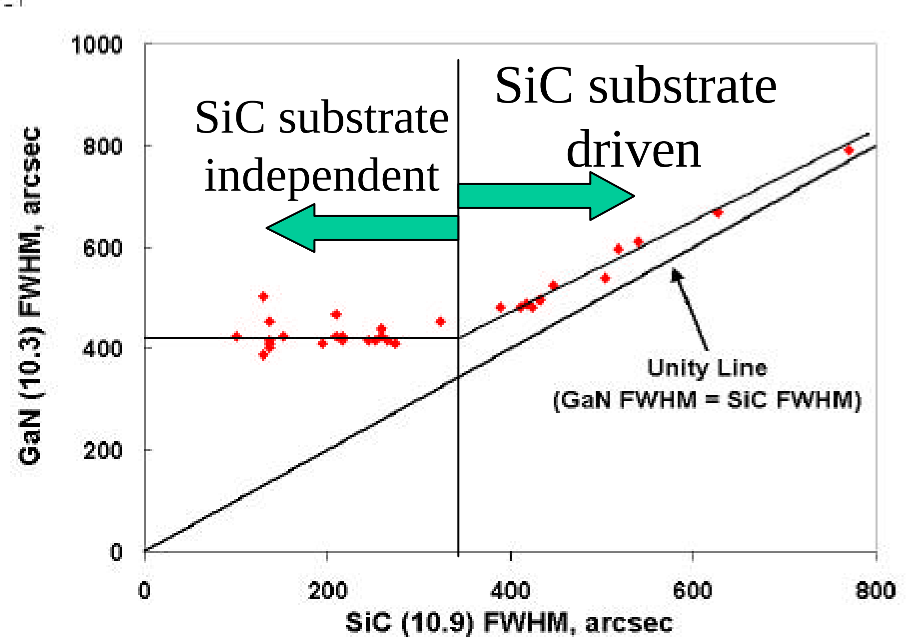
Semi-Insulating “High Purity” SiC (2)

- Ultra High Purity (UHP) semi-insulating SiC has reduced traps and higher thermal conductivity, BUT
  - smaller growth window
  - unestablished compensation mechanism (up to 5 trap levels reported)
  - possible deep level due to C-vacancy (analogous to EL2 in GaAs)
  - demonstrated enhancement in 4H-SiC MESFET performance

Material Quality-Device Correlation Not Established



X-ray map of 6H SiC wafer used for AlN/GaN epitaxy

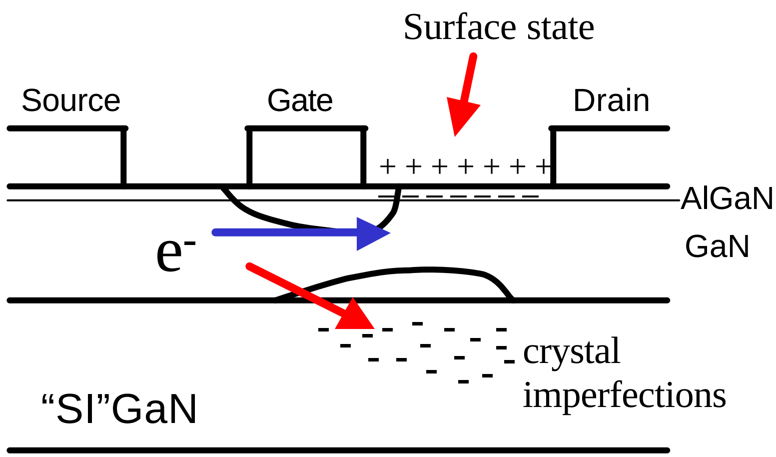


Correlation of SiC and GaN epi X-ray

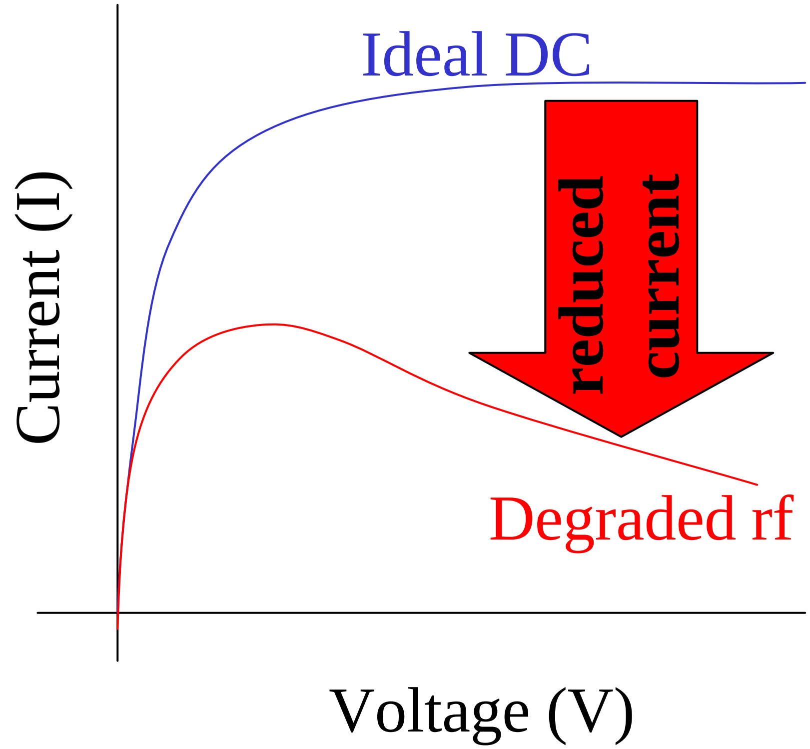
Epitaxial growth work supported ONR

Material Quality <u>and</u> Process Technology Dictates Device Performance

GaN Transistor

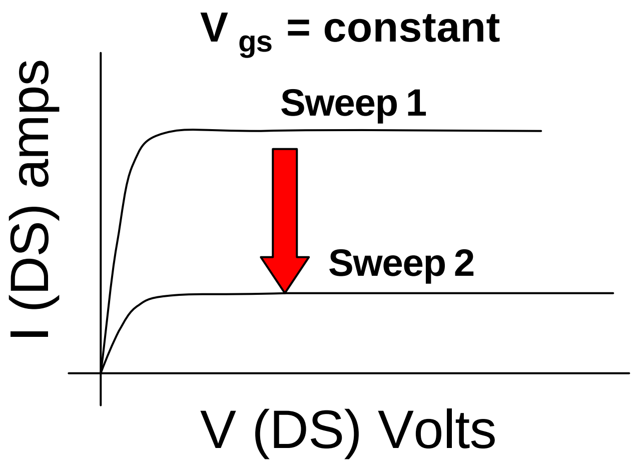


Surface states or crystal imperfections “trap” electrons and degrade RF current flow

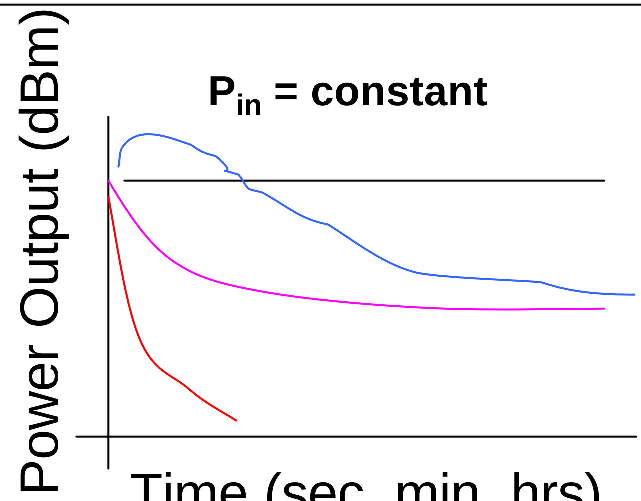


Strong polarization induced surface effect is minimized by silicon nitride passivation. Buffer traps determined by epitaxial growth conditions.

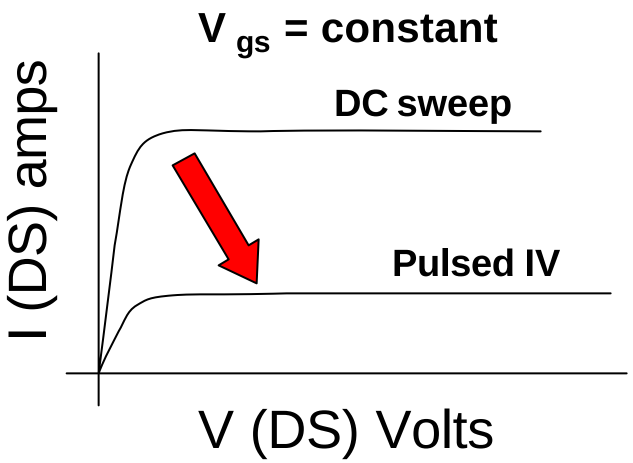
Changes in AlGaN HEMT Output versus Bias or Time



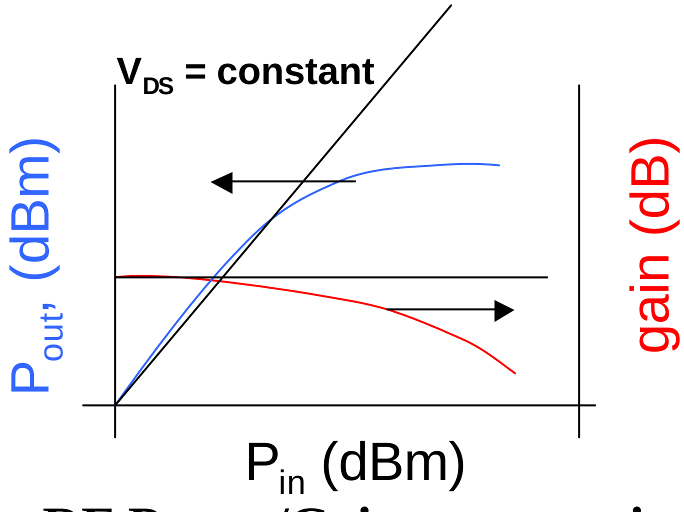
Current collapse (DC)



RF Power slump

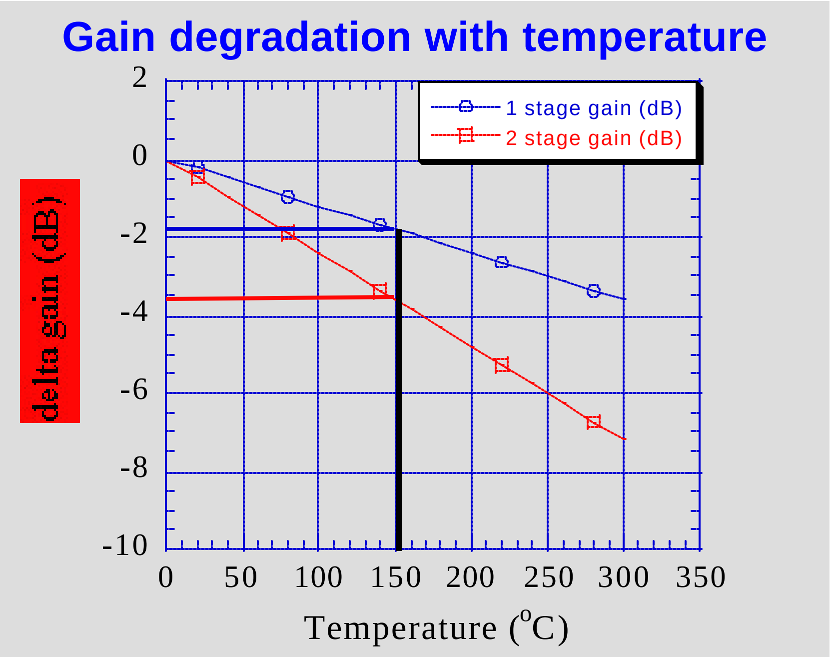


Current dispersion (DC to pulsed)



RF Power/Gain compression

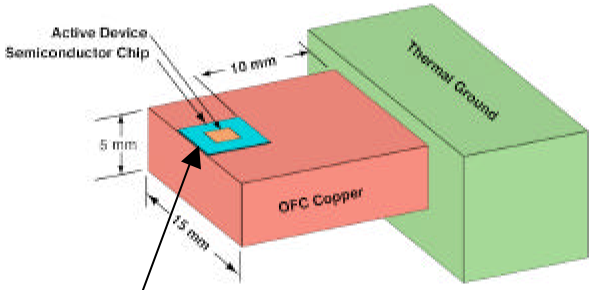
Increasing Temperature Limits RF Performance



Challenge:

New solutions are needed for cooling of high power density components – die, package, and module level solutions are needed

Conventional Cooling Approach



10x POWER IN SAME AREA

Wide Bandgap RF Technology Development Needs

- Increase quality (<10 upipe cm^{-2}), size (3 inch minimum), and availability of semi-insulating semiconductor substrates for wide bandgap devices
- Increase throughput and reproducibility of epitaxial device structures
- Establish correlation between wide bandgap RF device performance (and stability) and material/process technology.
- Improve manufacturing yield of substrates, epi, and amplifiers.
- Extend amplifier operating frequencies to 50 GHz and beyond
- Quantify and enhance component reliability (10^7 hr MTBF required)
- Develop packaging and thermal management approaches for up to 1 kW/cm^2.

Summary

- WBG enables improvements in RF transmitters (~10X in element power) for DoD unique applications with restricted aperture size that require enhanced sensitivity (PAG).
- Both SiC and AlGaN prototype devices have validated their predicted performance advantages.
- Stable, repeatable, materials and device technology is now required to move forward and transition into acquisition programs.